DEPARTMENT OF ENVIRONMENTAL QUALITY
STORAGE TANK DIVISION
PART 213, RISK-BASED SCREENING LEVELS (RBSLs)
FOR
GROUNDWATER AND SOIL VOLATILIZATION TO INDOOR AIR

INTRODUCTION

This Attachment 8 to Operational Memorandum No. 4 describes the technical development of Tier 1 Risk-Based Screening Levels (RBSLs) for groundwater and soil volatilization to indoor air inhalation criteria (GVIIC and SVIIC, respectively) for residential and commercial/industrial land use categories. These criteria are provided pursuant to sections 21304a(1)(2) of Part 213, Leaking Underground Storage Tanks (LUST), of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended. Section 21304a(2) requires the department to utilize only reasonable and relevant exposure assumptions and pathways in determining the cleanup criteria. The migration of contaminant vapors (i.e., in the gas or vapor phase) from groundwater and soil into buildings or other enclosed spaces, thereby exposing occupants in the building, is a relevant human exposure pathway that must be considered for unrestricted and restricted land use closures.

In the development of Tier 1 Lookup Tables, a Michigan Specific approach was used to take into account relevant Part 213 requirements for the utilization of the American Society for Testing and Materials (ASTM) Standard Guide for Risk-Based Corrective Action (RBCA), E 1739-95, which is adopted by reference in Part 213.

The GVIIC and SVIIC may be the controlling criteria at some facilities depending on the groundwater and soil characteristics, land use, and contaminants present. Therefore, generic scenarios were developed to generate GVIIC and SVIIC for use as a screening tool to identify sites which warrant further consideration of the indoor air inhalation pathway. In practice, these criteria serve as a reference point for interpreting the significance of potential health risks associated with the indoor air inhalation pathway. As such, these values can be used for determining whether a property is a facility under the provisions of Part 201, and are relevant in determining the adequacy of a corrective action plan (CAP). Application of the Tier 1 RBSLs GVIIC and SVIIC is intended to accelerate remedial decision-making, and facilitate the preparation, development and completion of CAPs. This operational memorandum is considered guidance in the application of the RBCA process as utilized by the Storage Tank Division. Other equivalent methods may be utilized. Additional guidance on the application and implementation of these criteria is presented in the latter part of this document.

⇒ **NOTE:** The Part 213 Tier 1 RBSLs for GVIIC and SVIIC are considered to be protective of only those health effects that may result from chronic inhalation exposure to hazardous substances. They do not represent levels that are protective of aesthetic characteristics such as odors, and are not protective of effects that may result from human intake or contact through other exposure pathways than inhalation. Inhalation exposures resulting from indoor uses of groundwater such as showering, laundry and cooking are also not considered. Additionally, these criteria may not be protective of physical hazards, such as flammability/explosivity, reactivity, corrosivity, and also ecological

impacts. An evaluation of the relevance of other exposure pathways and shorter term effects must be conducted to determine if more restrictive criteria are necessary for protecting these endpoints.

BACKGROUND AND CONCEPTUAL SITE MODEL

Much of the scientific research evaluating the migration of contaminant vapors into buildings has stemmed from efforts to address problems associated with the intrusion and accumulation of radon vapors. The mechanisms and factors affecting the transport of soil contaminant gases (vapors), primarily of volatile organic compounds (VOCs) into buildings are similar to those of radon. A review of the scientific literature on this issue shows that soil-gas entry into buildings is the result of both diffusive and convective transport processes, and that site-specific physical characteristics will determine the significance of each.

The Johnson and Ettinger (1991) model (JEM) was selected as the best available quantitative method for development of Part 213 Tier 1 RBSLs for GVIIC and SVIIC. Johnson and Ettinger developed a mathematical model to estimate diffusive and convective transport of contaminant vapors emanating from soil into indoor spaces. Because the JEM only describes contaminant vapors migration in soil, the migration of contaminants from groundwater (i.e., diffusion in a liquid phase instead of a vapor phase) was characterized using a methodology similar to that presented in the American Society for Testing and Materials (ASTM, 1995) for development of the RBSLs for GVIIC. The JEM is described in EPA's guidance document for Assessing Potential Indoor Air Impacts at Superfund Sites (EPA, 1992) and EPA's Soil Screening Guidance: Technical Background Document (EPA, 1996a), and is used by ASTM to guide risk-based corrective actions (RBCA) at petroleum release sites (ASTM, 1995).

JEM was chosen because it is a relatively simple mathematical computation for development of generic screening criteria, yet effectively represents the physical and chemical processes that influence the behavior of contaminant vapors in soil and groundwater. Moreover, model predictions from the JEM agree closely with those of a more sophisticated three-dimensional numerical model developed to predict the transport and intrusion of radon into buildings (Loureiro et al. 1990). The JEM is also widely used by EPA, ASTM and several other states for screening sites for this pathway. Lastly, the JEM was selected because simple site-specific measurements may be obtained and incorporated into the equations to derive site-specific criteria.

The modeling of contaminant transport through soil and into buildings is a complex process. As contaminants move from the source to soil vapor to building vapor, a number of factors influence the amount of contamination that migrates from one location to the next. These factors are accounted for in the equilibrium partitioning calculations and the models attenuation coefficient. Overall, the JEM consists of five fundamental steps.

Step 1: Calculation of the Ratio of the Soil Vapor Phase Concentration to Total Concentration at the Source Ratio

This step estimates a concentration ratio, CR_{source}, which relates the vapor phase concentration of contaminant in the soil pore air spaces to the ***"total"*** concentration present in the soil or groundwater. The total concentration of a chemical in soil is equal to the amount present in three phases: 1) vapor in pore air, 2) dissolved in pore water, and 3) sorbed to soil particles. In soil, this ratio is calculated considering the interaction of the physicochemical properties of the chemical with physical properties of the soil, referred to as equilibrium partitioning. For groundwater, the ratio is determined assuming that

the vapor phase concentration in the overlying soil is in equilibrium with the aqueous phase concentration as a function of the Henry's Law Constant.

Step 2: Calculation of the Effective Diffusion Coefficient

This step involves determination of the chemical-specific effective diffusion coefficient (D^{eff}) in soil or groundwater. Diffusion represents the rate of contaminant flow through soil and/or groundwater, which occurs through both pore air and pore water. In general, the D^{eff} accounts for chemical-specific and medium-specific characteristics that act to reduce contaminant flow, a process collectively known as tortuosity. The partitioning behavior of contaminants between phases (liquid, solid and gas) as they flow through interconnected pore spaces also influences contaminant diffusion.

Calculation of the D^{eff} for groundwater is more involved than for soil in that diffusion of the contaminant through the capillary fringe to the overlying soil must be considered. The capillary fringe is a predominantly water saturated zone located between the groundwater table and the unsaturated zone. An approach similar to that presented in ASTM (1995) RBCA was used. This is required since the JEM is designed to predict transport of contaminant vapors only through soil. Therefore, modeling the diffusion of water-borne contaminants as vapors through the capillary fringe is performed to yield the soil vapor phase levels required for input into the JEM.

Step 3: Calculation of the Infiltration Rate of Contaminant Vapors into the Building

Next, the emission or infiltration rate of vapors through cracks in the concrete floor/walls is estimated. This value is first dependent on the amount of contaminant transported via diffusion from the source to the building. The infiltration rate of vapors into the building is then a function of the total crack area, building pressurization relative to the surrounding soil, and the soil vapor permeability in the "zone of influence". The zone of influence represents the distance from the building shell (below grade) to a point in the soil where convective forces are no longer acting to sweep contaminant vapors toward cracks in the subgrade portion of the building. The magnitude of the indoor-outdoor pressure differential, area of the cracks, and soil vapor permeability will collectively determine the extent of the zone of influence, hence the vapor intrusion rate into the building.

Step 4: Calculation of the Building Vapor Concentration to Total Soil or Groundwater Vapor Source Concentration Ratio

This step estimates another concentration ratio, $CR_{building}$, which relates the indoor vapor concentration in the building to the vapor phase concentration at the source, determined in Step 1 above. The factors that influence this ratio are the factors associated with Steps 2 and 3 above, and the building volume and indoor air ventilation rate.

Step 5: Back-calculation of the GVIIC and/or SVIIC

An acceptable total concentration in soil (ug/kg) or groundwater (ug/l) is determined in this step. Given the acceptable indoor air concentration that a human may be exposed to daily without adverse health effects, and the building vapor concentration generated per unit soil or groundwater concentration the corresponding GVIIC or SVIIC is calculated. The acceptable indoor air concentration is based on the generic land-use specific exposure assumptions and the toxicity characteristics of the contaminant.

⇒ **NOTE:** The JEM may be used to solve both steady state (i.e., infinite source) and quasi-steady state (i.e., finite source) conditions for contaminants in soil. Finite source modeling is not feasible for generic modeling of groundwater contaminant volatilization to indoor air since the location, medium and volume of source cannot be standardized. Therefore, only a methodology for calculating finite source-based SVIIC is provided.

The generic conceptual site models (CSM) used to develop the Tier 1 RBSLs residential and commercial/industrial GVIIC and SVIIC are illustrated in Figure 1 and 1a. Some of the physical attributes that were considered characteristic of the residential and commercial/industrial land use categories are shown, as well as the key parameters of the JEM used to calculate the Tier 1 RBSLs .

Residential Land Use Scenario

A single family detached home is the predominant residential housing type (EPA, 1996b). Information contained in a report entitled *Characteristics of New Housing: 1995* (U.S. DOC and U.S. HUD, 1996) was reviewed to determine a representative generic residential home size and construction type for houses in Michigan. This review found that 90% of homes built in the Midwest between 1975 and 1995 have basements or crawl spaces. Therefore, a single story house (ranch) with a basement was assumed for Tier 1 RBSL calculations. The size of single family residences in the Midwest has increased steadily from an average low of 1,645 ft^2 (floorspace area) in 1975 to an average high of 2,095 ft^2 in 1995. House size is a sensitive input into the JEM as it influences the potential total crack area available for vapor infiltration and the total volume of air for contaminant mixing and ventilation. A frequency distribution of the floorspace range for residential homes built in 1995 is provided in the table below.

Size	Percentage of Homes
Under 1,200 ft^2	11%
1,200 to 1,599 ft^2	23%
1,600 to 1,999 ft^2	23%
2,000 to 2,399 ft^2	18%
2,400 to 2,999 ft^2	14%
Greater than 3,000 ft^2	11%

Based on this range, 1,200 ft^2 (111.5 m^2) was selected as an upper percentile estimate (approximately 90th percentile) for Tier 1 RBSL residential calculations. Applying two eight-foot ceilings yields a total indoor air volume of 19,200 ft^3, or 544 m^3.

⇒ **NOTE:** For the Tier 1 residential scenario, the soil contaminant source is assumed to lie directly below the foundation floor, while contaminants in groundwater are assumed to be present 100 centimeters below the foundation floor.

Commercial/Industrial Land Use Scenario

The commercial and industrial land use categories were grouped together since the operations at the majority of industrial land uses involve separate spaces/rooms that typically adjoin, or are located next to the main industrial building(s). These spaces or buildings are generally similar in size, type and ventilation to many other commercial structures. Therefore, the Tier 1 RBSL SVIIC and GVIIC for commercial and industrial land use categories were consolidated into one set of criteria that reflects a

common receptor population to both land use types, and that will assure protection of that portion of the population that would likely experience the greatest amount of contaminant exposure.

Choice of the generic commercial building size (floorspace area) and type was guided by a report entitled *Commercial Buildings Characteristics 1992* which documents the results of a Commercial Buildings Energy Consumption Survey (CBECS) conducted by the U.S. Department of Energy (DOE, 1994). This survey is completed on a triennial basis and provides a wide range of statistics related to physical commercial building characteristics on a national and regional scale. Building size and other variables measured in the survey are estimates based on reported data from a randomly chosen subset of the entire population of commercial buildings. Data from nearly 6,600 buildings nationwide were obtained.

Commercial building activities/operations span a wide range, however, the majority of buildings are generally similar in size. As shown in the table below, over 50% of the commercial buildings have a floor area between 1,000 and 5,000 ft^2, with the remaining percentage of buildings greater than 5,000 ft^2.

	Number of Buildings
Building Floorspace (ft^2)	**East North Central U.S. (Includes Michigan)**
1,001 to 5,000	422
5,001 to 10,000	149
10,001 to 25,000	104
25,001 to 50,000	37
50,001 to 100,000	22
100,001 to 200,000	9
200,001 to 500,000	5
Over 500,000	1
Total:	749

In addition, the CBECS survey reports that 381 of the 749 buildings are single floor construction types. The three most common commercial building activities, listed in order of most frequent occurrence, are categorized as 'Mercantile and Service', 'Warehouse and Storage', and 'Office.' The floorspace areas for these building categories was not provided by region. However, the nationwide reported ***median*** floorspace areas for the three categories is 4,000, 5,000 and 5,000 ft^2, respectively. The median statistic instead of the mean is the most appropriate measure of central tendency in this instance as the distribution for this variable is skewed toward commercial building sizes at the low end of the range (i.e., 1000 to 5000 ft^2, see table above).

The nationwide median and mean floorspace area for a number of other building activities are shown below.

Building Activity	**Number of Buildings**	**Mean ft^2 (thousand)**	**Median ft^2 (thousand)**
Education	301	28.2	9.0
Food Sales	130	5.8	2.6
Food Service	260	5.7	3.4
Health Care	63	27.9	4.3
Lodging	154	18.8	8.0

Mercantile and Service	***1,272***	***9.7***	***4.0***
Office	749	16.4	5.0
Public Assembly	278	16.4	5.9
Public Order and Safety	60	13.7	5.0
Religious Worship	366	10.2	4.4
Warehouse and Storage	761	15.1	5.0
Other	69	16.4	4.0
Vacant	319	13.8	4.2

The 'Mercantile and Service' category includes buildings such as gasoline service stations, automobile dealers, department stores, furniture stores, multi-retail establishments, laundry and dry cleaners, post offices, and shopping malls. This category was selected to represent the generic building size and floorspace area for development of commercial/industrial SVIIC and GVIIC. Only 'Food Sales' and 'Food Service' buildings have lower median values. Therefore, 4,000 ft^2 (372 m^2) is the commercial/industrial building size default floorspace area. The total indoor air volume, considering one floor with an eight foot ceiling, is 908 m^3.

⇒ **NOTE:** The soil contaminant source is considered to be located directly below the foundation floor, and groundwater is assumed to be present 3 meters (300 cm) below the foundation, which is assumed to be at grade level.

Other attributes of the generic scenarios are identified and explained in the following section.

JEM Assumptions

There are a number of assumptions underlying the JEM. These characteristics are assumed to apply in the calculation of the SVIIC and GVIIC and do not need to be confirmed on a site-specific basis.

- The contaminant is homogeneously distributed within the soil or groundwater source.
- Soil is homogeneous such that the effective diffusion coefficient is constant.
- Contaminant loss from leaching downward does not occur.
- Source degradation and transformation is not considered.
- Contaminant concentration at the interface between the soil particle surface and soil pore air space is zero (i.e., boundary layer resistance is zero).
- Convective vapor flow near the building foundation is uniform.
- Convective vapor flow rates decrease with increasing distance between the contaminant source and the building.
- Contaminant vapors enter the building through openings in the walls and foundation at or below grade.
- Both the building ventilation rate and the difference in pressure between the building interior and the surrounding soil are constant.
- All contaminant vapors directly below the building will enter the building, unless the floor and walls are perfect vapor barriers.
- The building contains no other contaminant sources or sinks, and contaminant vapor dispersion is instantaneous and homogeneous.

TECHNICAL DEVELOPMENT AND TIER 1 RBSL EQUATIONS

Equations 1 through 4 are used to calculate chemical-specific SVIIC and GVIIC for carcinogenic and noncarcinogenic contaminants. Chemical-specific ***soil*** concentrations protective of unacceptable indoor air inhalation risks are calculated as follows:

Carcinogens

$$SVIIC = \frac{TR \times AT \times AIR}{IURF \times EF \times ED \times CR_{building}} \quad (1)$$

where,

SVIIC	(Soil Volatilization Indoor Air Inhalation Criteria)	= chemical-specific, ug/kg
TR	(Target risk)	= 1E-5
AT	(Averaging time)	= 25,550 days (70 x 365)
AIR	(Adjusted inhalation rate)	= 1 (Residential; [(20m^3/day)/(20m^3/day)])
		= 2 (Commercial/Industrial; [(20m^3/day)/(10m^3/day)]
IURF	(Inhalation unit risk factor)	= chemical-specific, (ug/m^3)$^{-1}$
EF	(Exposure frequency)	= 350 days/year (Residential)
		= 245 days/year (Commercial/Industrial)
ED	(Exposure duration)	= 30 years (Residential)
		= 21 years (Commercial/Industrial)
$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, (ug/m^3)/(ug/kg)*

Noncarcinogens

$$SVIIC = \frac{THQ \times AT}{(1/RfC) \times EF \times ED \times CR_{building}} \quad (2)$$

where,

SVIIC	(Soil Volatilization Indoor Air Inhalation Criteria)	= chemical-specific, ug/kg
THQ	(Target hazard quotient)	= 1
AT	(Averaging time)	= 10,950 days (Residential)
		= 7,665 days (Commercial/Industrial)
EF	(Exposure frequency)	= 350 days/year (Residential)
		= 245 days/year (Commercial/Industrial)
ED	(Exposure duration)	= 30 years (Residential)
		= 21 years (Commercial/Industrial)
RfC	(Reference concentration)	= chemical-specific, ug/m^3
$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, (ug/m^3)/(ug/kg)*

* $CR_{building}$ is expressed as a concentration ratio which relates the indoor air vapor concentration (ug/m^3) to the vapor-phase concentration at the soil, CR_{source}^{soil}, or groundwater, CR_{source}^{gw}, source. CR_{source}^{soil} and CR_{source}^{gw} are also concentration ratios and are defined below.

Chemical-specific ***groundwater*** concentrations protective of unacceptable indoor air inhalation risks are:

Carcinogens

$$GVIIC = \frac{TR \times AT \times AIR}{IURF \times EF \times ED \times CR_{building}} \quad (3)$$

where,

GVIIC	(Groundwater Volatilization Indoor Air Inhalation Criteria)	= chemical-specific, ug/l
TR	(Target risk)	= 1E-5
AT	(Averaging time)	25,550 days (70 x 365)
AIR	(Adjusted inhalation rate)	= 1 (Residential; [(20m^3/day)/(20m^3/day)])
		= 2 (Commercial/Industrial; [(20m^3/day)/(10m^3/day)])
IURF	(Inhalation unit risk factor)	= chemical-specific, (ug/m^3)$^{-1}$
EF	(Exposure frequency)	= 350 days/year (Residential)
		= 245 days/year (Commercial/Industrial)
ED	(Exposure duration)	= 30 years (Residential)
		= 21 years (Commercial/Industrial)
$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, (ug/m^3)/(ug/l)*

Noncarcinogens

$$GVIIC = \frac{THQ \times AT}{(1/RfC) \times EF \times ED \times CR_{building}} \quad (4)$$

where,

GVIIC	(Groundwater Volatilization Indoor Air Inhalation Criteria)	= chemical-specific, ug/l
THQ	(Target hazard quotient)	= 1
AT	(Averaging time)	= 10,950 days (Residential)
		= 7,665 days (Commercial/Industrial)
EF	(Exposure frequency)	= 350 days/year (Residential)
		= 245 days/year (Commercial/Industrial)
ED	(Exposure duration)	= 30 years (Residential)
		= 21 years (Commercial/Industrial)
RfC	(Reference concentration)	= chemical-specific, ug/m^3
$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, (ug/m^3)/(ug/l)*

* $CR_{building}$ is expressed as a concentration ratio which relates the indoor air vapor concentration (ug/m^3) to the vapor-phase concentration at the soil, CR^{soil}_{source}, or groundwater, CR^{gw}_{source}, source. CR^{soil}_{source} and CR^{gw}_{source} are also concentration ratios and are defined below.

Toxicity Values and Exposure Assumptions

Note that the reference concentrations (RfC) and inhalation unit risk factor (IURF) toxicity values are presented as concentrations in air (ug/m^3). Because these values are assumed to be protective of sensitive subgroups of the population, it is not necessary to incorporate body weight or the inhalation rate into the equations. In addition, these values are set to be protective against continuous exposures. Because continuous exposure is not characteristic of worker exposures in commercial and industrial settings an adjustment is necessary to account for the volume of air intake for an on-site worker. Therefore, an adjusted intake rate (AIR) of 20 m^3/day /10 m^3/day (i.e., a factor of 2) was added to the commercial/industrial GVIIC and SVIIC equations. The AIR is applied only to carcinogenic chemicals for consistency with currently proposed Air Quality Division administrative rules. The 10 m^3/day intake rate for workers is consistent with both EPA and Occupational Safety and Health Administration (OSHA) standard default values and assumes that a worker engaged in moderate activity will respire more heavily while on the job than during light activity and resting portions of a day.

The default values for EF and ED are the same as those used in the Part 213 algorithms for calculating the health-based drinking water values, since the same receptor population (i.e., resident or worker) is also present in a building for the same amount of time breathing indoor air.

Building Indoor Air Vapor Concentration to Groundwater or Soil Vapor Concentration

The ratio of the indoor vapor concentration to the source vapor concentration is calculated as the product of the vapor phase concentration at the source to the total source concentration ratio and the attenuation coefficient:

$$CR_{building} = CR_{source}^{soil/gw} \times \alpha \qquad (5)$$

where,

$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, units noted above for groundwater and soil
α	(Attenuation coefficient)	= chemical-specific, unitless
$CR_{source}^{soil/gw}$	(Ratio of vapor phase concentration to total soil or groundwater source concentration)	= chemical-specific, units given below

Vapor-phase Concentration to Total Source Concentration Ratio

The ratio of the ***"vapor-phase"*** contaminant concentration to the ***"total"*** concentration at the source for soil (CR_{source}^{soil}) is calculated differently than for groundwater (CR_{source}^{gw}), since equilibrium conditions for a given contaminant are reached differently in soil than in water. Under equilibrium conditions in soil contaminant levels in the vapor, soil moisture (i.e., water), and sorbed phases are assumed to be proportional to each other and the total contaminant level. This is a conservative assumption as complete and constant equilibrium of all chemical physical states is rarely attained since standard temperature and pressure conditions under which the equilibrium constants are measured do not remain constant in the environment. For these calculations it is also assumed that no residual contaminant is present in the soil pores as free liquid or precipitate (solid). The ratio of the vapor phase concentration to the unit source contaminant concentration (i.e., 1 ug/kg) for soil is written as:

$$CR_{source}^{soil} = \frac{H' \times TAF \times C_s \times \rho_b \times 10^{-3}\,kg/g \times 10^{6}\,cm^3/m^3}{\theta_w + (k_d \times \rho_b) + (H' \times TAF \times \theta_a)} \qquad (6)$$

where,

CR_{source}^{soil}	(Ratio of vapor phase concentration to total soil source concentration)	= chemical-specific, (ug/m^3)/(ug/kg)*
H'	(Dimensionless Henry's law constant)	= chemical-specific, unitless (HLC x 41)
TAF	(Temperature adjustment factor)	= 0.5 (HLC adjusted to Michigan annual average soil temperature of 10° Celsius)
C_s	(Uniform concentration in soil)	= 1 ug/kg
ρ_b	(Dry Soil Bulk Density)	= 1.5 g/cm^3 (EPA, 1996a)
θ_w	(Soil water-filled porosity)	= 0.3 cm^3/cm^3 (EPA, 1996a)
k_d	(Soil-water Partition Coefficient)	= chemical-specific, cm^3/g
	Organic Compounds	= K_{oc} (chemical-specific, cm^3/g) x f_{oc} (0.002)
θ_a	(Soil air-filled porosity)	= 0.13 cm^3/cm^3 (EPA, 1996a)

This ratio is developed considering the partitioning characteristics of the chemical in conjunction with the soil properties, such as the organic carbon content of the soil (f_{oc}). For purposes of back-calculation a uniform unit (1 ug/kg) concentration in soil is assumed.

Consistent with the development of soil-water partitioning criteria (MDEQ, 1997a), soil property default values representative of a loam soil type and subsurface conditions were used as provided by EPA (1996a). The chemical-specific dimensionless Henry's Law Constants (HLC) are multiplied by one-half (0.5) to account for reduced volatility of the contaminant under lower annual average soil temperatures of 10° Celsius in Michigan, relative to the measured HLCs reported at 25^0 Celsius (Howe et al., 1987). The soil-organic carbon partition coefficients (K_{oc}) were calculated using regression analyses relating K_{oc} values to octanol-water partition coefficients (K_{ow}) as presented in EPA (1996a) guidance, and also in previous MDEQ (1997b) guidance.

The vapor concentration for contaminants in ***groundwater*** is assumed to be in equilibrium with the aqueous phase concentration. This equilibrium condition is a function of the dimensionless Henry's Law Constant (also adjusted for Michigan soil temperature). The concentration ratio relating the vapor phase concentration in the soil pore air, overlying the groundwater, to the total groundwater source concentration is given by the following equation:

$$CR_{source}^{gw} = \left(H' \times TAF\right) \times C_w \times 10^3 l / m^3 \qquad (7)$$

* CR_{source}^{soil} is expressed as a concentration ratio relating the vapor-phase contaminant concentration generated per unit contaminant concentration in soil (ug/kg).

where,

CR_{source}^{gw}	(Ratio of vapor phase concentration to total groundwater source concentration)	= chemical-specific, (ug/m^3)/(ug/l)*
H'	(Dimensionless Henry's law constant)	= chemical-specific, unitless (HLC x 41)
TAF	(Temperature adjustment factor)	= 0.5 (HLC adjusted to Michigan annual average soil temperature of 10° Celsius)
C_w	(Uniform concentration in groundwater)	= 1 ug/l

As in the soil calculation, a uniform unit concentration in water (1 ug/l) is assumed for purposes of back-calculating the GVIIC..

ATTENUATION COEFFICIENT

The attenuation coefficient calculation is the core equation of the JEM. In general, the attenuation coefficient (α) is estimated as the ratio of contaminant vapor concentration in the building to the vapor concentration present at the source. To derive this ratio, the JEM accounts for certain key chemical and physical factors that influence vapor transport from the contaminant source into a building.

Transport of contaminant vapor from the source through the soil pores, or in the case of groundwater through the capillary fringe, to a building occurs as the result of molecular diffusion. Entry of contaminant vapors from the surrounding soil into the building may occur by diffusion, but can also occur through convective transport. Convective transport, or literally the drawing in of vapors, occurs as the result of pressure differences across the building shell. The JEM couples both diffusive and convective transport mechanisms into an analytical solution that predicts chemical-specific attenuation coefficients. Values of α for soil can be derived for both steady state conditions (i.e., infinite contaminant source) and quasi-steady state conditions (i.e., given a finite source thickness). Values of α for groundwater are calculated assuming only infinite source conditions. For infinite source conditions α is written as follows for soil and groundwater:

$$\alpha = \frac{\left[\left[\frac{D^{eff} A_b}{Q_{building} L_T}\right] \times \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)\right]}{\left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) + \left[\frac{D^{eff} A_b}{Q_{building} L_T}\right] + \left[\frac{D^{eff} A_b}{Q_{soil} L_T}\right]\left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) - 1\right]\right]} \quad (8)$$

* CR_{source}^{gw} is expressed as a concentration ratio relating the vapor-phase contaminant concentration generated per unit contaminant concentration in groundwater (ug/l).

where,

α	(Attenuation coefficient)	= unitless
D^{eff} *	(Effective diffusion coefficient)	= chemical-specific, cm^2/s
D^{crack} *	(Effective diffusion coefficient through crack)	= cm^2/s, (D^{crack} = D_v^{eff} , see equation 9)
A_b **	(Area of enclosed space below grade)	= 1.96E+6 cm^2 (Residential) = 3.72E+6 cm^2 (Commercial/Industrial)
$Q_{building}$ **	(Building ventilation rate)	= 1.51E+5 cm^3/s (Residential) = 5.04E+5 cm^3/s (Commercial/Industrial)
L_{crack}	(Building foundation thickness)	= 15 cm
L_T	(Source-building separation distance)	= 15 cm (soil) = 115 cm (groundwater-Residential = 300 cm (groundwater- Commercial/Industrial)
Q_{soil} **	(Volumetric flow rate of soil vapor into the building)	= 0.81 cm^3/s (Residential) = 2.09 cm^3/s (Commercial/Industrial)
A_{crack}	(Total area of cracks below grade)	= 196 cm^2 (Residential) = 372 cm^2 (Commercial/Industrial)
exp(p)	(The base of the natural logarithm raised to power p)	= e^p

* When calculating the value of α for soils, use the D_v^{eff} from equation 9. When calculating the value of α for groundwater, use the D_T^{eff} from equation 10.

** Calculated default inputs rounded to two significant figures for calculation of the criteria.

Effective Diffusion Coefficient

The chemical-specific effective diffusion coefficients for the SVIIC (D_v^{eff}) and GVIIC (D_T^{eff}) describe the rate of vapor flow using simple Fickian diffusion modeling. Diffusion occurs in the both the pore air and pore water spaces through a tortuous path. This is accounted for in the calculation by applying a tortuosity factor defined by the Millington-Quirk model (Farmer et al., 1972) to the air- and water-filled porosity values. Therefore, ***in soil*** the rate of diffusion is dependent on the soil and chemical-specific characteristics as noted in the equation below:

$$D_v^{eff} = D_a\left(\theta_a^{3.33}/n^2\right) + \frac{D_w}{H'\times TAF}\left(\theta_w^{3.33}/n^2\right) \qquad (9)$$

where,

D_v^{eff}	(Effective diffusion coefficient for vadose zone)	= chemical-specific, cm^2/s
D_a	(Diffusivity in air)	= chemical-specific, cm^2/s
θ_a	(Soil air-filled porosity)	= 0.13 cm^3/cm^3
n	(Total soil porosity)	= 0.43 cm^3/cm^3

D_w	(Diffusivity in water)	= chemical-specific, cm^2/s
θ_w	(Soil water-filled porosity)	= 0.3 cm^3/cm^3
H'	(Dimensionless Henry's Law Constant)	= chemical-specific, unitless (HLC x 41)
TAF	(Temperature adjustment factor)	= 0.5 (HLC adjusted to Michigan annual average soil temperature of 10° Celsius)

Calculation of the effective coefficient for a contaminant ***in groundwater*** is more complex, since contaminant transport must be modeled across two different strata the saturated (i.e., capillary fringe) and unsaturated (i.e., vadose zone) zones. The capillary fringe is a nearly saturated zone located directly above the top of the water table, where groundwater is held within the soil pores at less than atmospheric pressure (Freeze and Cherry, 1979). The vadose zone, above the capillary fringe, has a lower soil moisture content and a greater amount of connected air-filled pore spaces. Chemical diffusivity through water is approximately four orders of magnitude lower than through air. To account for the variation in chemical diffusivity across these two zones a total overall effective diffusion coefficient (D_T^{eff}) is calculated as:

$$D_T^{eff} = \frac{L_T}{\left(h_v + L_{crack} / D_v^{eff}\right) + \left(h_{cf} / D_{cf}^{eff}\right)} \qquad (10)$$

where,

D_T^{eff}	(Overall or average effective diffusion coefficient)	= chemical-specific (cm^2/s)
L_T	(Source-building separation distance)	= 115 cm (Residential) = 300 cm (Commercial/Industrial)
h_v	(Thickness of vadose zone below enclosed space floor)	= 75 cm (Residential) = 260 cm (Commercial/Industrial)
L_{crack}	(Building foundation thickness)	= 15 cm
D_v^{eff}	(Effective diffusion coefficient through vadose zone; see equation 9)	= chemical-specific (cm^2/s)
h_{cf}	(Thickness of capillary fringe)	= 25 cm
D_{cf}^{eff}	(Effective diffusion coefficient through capillary fringe; see equation 11 below)	= chemical-specific (cm^2/s)

The thickness of the capillary fringe (h_{cf}) is considered to be equal to the height of capillary rise in a tube for a specific soil material (e.g., sand, silt and clay) and grain size. Although it is recognized that pore space openings and size vary considerably, such that capillary rise is not a straight line above the groundwater table, a standard value must be chosen for development of criteria.

Attachment 1 presents data for capillary rise values according to soil material and grain size from two separate reference sources. The data from the two sources show remarkable consistency. However, for simplicity, the most recent reference was chosen as the basis for the default h_{cf} value. Because the soil "materials" listed are not soil "types," the selection of which soil material to represent the generic loam soil is not straightforward. Gravel is not considered a soil material of sandy loam, so "fine gravel" was eliminated from the analysis. Upon elimination of fine gravel values range from 4 to 750 cm, with a median or 50th percentile value of 50 cm and an upper-percentile value of 15 cm. However, it is not likely that "coarse sand" (15 cm) would predominate at many sites as an isotropic soil material, as

assumed by the Johnson and Ettinger model. Because h_{cf} is a sensitive parameter for development of the GVIIC a low to mid-range value was selected as a default value. A default value of 25 cm (10 inches) represented by "medium sand" was selected for h_{cf}

This parameter may be modified for calculation of a site-specific Tier 2 RBSL provided that site data support a greater value for h_{cf}

The effective diffusion coefficient to characterize vapor migration through the capillary fringe is determined as follows:

$$D_{cf}^{eff} = \left[D_a\left(\theta_{a,cf}^{3.33}/n^2\right)\right] + \left[\frac{D_w}{H'\times TAF}\left(\theta_{w,cf}^{3.33}/n^2\right)\right] \qquad (11)$$

where,

D_{cf}^{eff}	(Effective diffusion coefficient for capillary fringe)	= chemical-specific, cm^2/s
D_a	(Diffusivity in air)	= chemical-specific, cm^2/s
$\theta_{a,cf}$	(Soil air-filled porosity in capillary fringe)	= 0.078 cm^3/cm^3
D_w	(Diffusivity in water)	= chemical-specific, cm^2/s
H'	(Dimensionless Henry's Law Constant)	= chemical-specific, unitless (HLC x 41)
TAF	(Temperature adjustment factor)	= 0.5 (HLC adjusted to Michigan average soil temperature of 10° Celsius)
$\theta_{w,cf}$	(Soil water-filled porosity in capillary fringe)	= 0.352 cm^3/cm^3
n	(Total soil porosity)	= 0.43 cm^3/cm^3

As noted above, the capillary fringe is a predominantly saturated zone directly above the water table. The water content of the soil varies between drainage and wetting cycles, but is always less than completely water-filled which would equal the total porosity. This results from air entrapment in the pores during the wetting process (Gilham, 1984). Freijer (1994) found that vapor-phase diffusion coefficients were practically zero after soil samples were saturated with water, indicating that all remaining air-filled soil pores are disconnected and unavailable for vapor diffusion. However, as the air-filled porosity increases, the diffusion coefficients increased indicating the presence of connected air-filled pores. This minimum air-filled porosity at which the pores become interconnected is defined as the "air-entry pressure head". The air-entry pressure head corresponds with the top of the tension saturated zone within the capillary fringe.

To account for the variation in air content throughout the capillary fringe, and for calculating contaminant transport via both liquid and vapor -phase diffusion, the $\theta_{w,cf}$ is calculated at the air-entry pressure head (h) according to the van Genuchten soil water retention curve equation (as cited in Carsel and Parrish, 1988) which expressed as:

$$\theta_{w,\,cf} = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left(\alpha h\right)^N\right]^{-M}} \qquad (12)$$

where the default values used to calculate $\theta_{w,cf}$ are the mean values for the van Genuchten soil water retention parameters for the loam soil type, and are given in Attachment 2.

$\theta_{w,cf}$	(Soil water-filled porosity in capillary fringe)	= 0.352 cm^3/cm^3
θ_r	(Residential soil water content)	= 0.078 cm^3/cm^3
θ_s	(Saturated soil water content)	= 0.43 cm^3/cm^3
α	(Point of inflection in the water retention curve where $d^{\theta} w/d^h$ is maximal)	= 0.036 cm^{-1}
h	(Air-entry pressure head, $^h = 1/^{\alpha}$)	= 27.778 cm
N	(van Genuchten curve shape parameter)	= 1.56 dimensionless
M	M=1-(1/N)	= 0.359 dimensionless

Using the calculated value of $\theta_{w,cf}$ within the capillary fringe at the air-entry pressure head, the air-filled porosity within the capillary fringe ($\theta_{a,cf}$ is calculated as the total porosity (n) minus $\theta_{w,cf}$ (i.e., 0.078 cm^3/cm^3. Carsel and Parrish (1988) developed mean values of the van Genuchten soil water retention curve parameters for the 12 Soil Conservation Service (SCS) soil textural classifications. The database used to develop the mean values for the van Genuchten soil water retention curve parameters was developed from sampling data representing 42 states and range from sample populations sizes of 46 to 1,183. With these data, defaults may be estimated for $\theta_{w,cf}$ and $\theta_{a,cf}$ for each soil classification.

Effective Diffusion Coefficient Through Building Cracks (D^{crack})

The JEM assumes that the floor/wall cracks are filled with soil characterized by the density, porosity and moisture content of the underlying soil. Therefore, the effective diffusion coefficients through cracks (D^{crack}) are equal to their corresponding D_v^{eff} as calculated in equation 9 above.

Area of Building Below Grade (A_b)

This parameter represents the cross-sectional area of the building that lies below ground surface. This value is therefore considered to represent the total subgrade building area (i.e., the area of the building structure that is below grade in contact with subsurface soil) through which vapors pass; it is sometimes referred to as the vapor infiltration area. For the Tier 1 RBSL residential scenario this value is equal to the total basement area, floor and walls, that are below grade. It is also assumed that the foundation floor lies 200 centimeters (6.6 ft) below grade. Recall that the residential floorspace default value is 1200 ft^2 (1.1E+6 cm^2 ; 1 ft^2 = 0.0929 m^2 = 929 cm^2). Since the generic commercial/industrial building is a slab-on-grade construction, only the foundation floor is considered to lie below grade (i.e., 15 cm, or approximately 6 inches). The total floor space area for the commercial/industrial is 4,000 ft^2. Given these default values, A_b is calculated as follows:

$$A_b = L_b \times W_b + [2(L_F \times L_b) + 2(L_F \times W_b)] \qquad (13)$$

where,

A_b	(Area of building below grade)	= 1.96E+6 cm^2 (Residential) = 3.72E+6 cm^2 (Commercial/Industrial)
L_b	(Building floor length)	= 1056 cm (Residential) = 1928 cm (Commercial/Industrial)
W_b	(Building floor width)	= 1056 cm (Residential) = 1928 cm (Commercial/Industrial)
L_F	(Depth below grade to bottom of enclosed space floor)	= 200 cm (Residential) = 15 cm (Commercial/Industrial)

Building Ventilation Rate ($Q_{building}$)

The building ventilation rate is expressed as the volumetric flow rate of air through the building. It is calculated as the product of the total building volume and an "air-exchange rate" (ACH):

$$Q_{building} = \frac{L_b \times W_b \times H_b \times ACH}{3600 s / hr} \quad (14)$$

where,

$Q_{building}$	(Building ventilation rate)	= 1.51E+5 cm^3/s (Residential) = 5.04E+5 cm^3/s (Commercial/Industrial)
L_b	(Building floor length)	= 1056 cm (Residential) = 1928 cm (Commercial/Industrial)
W_b	(Building floor width)	= 1056 cm (Residential) = 1928 cm (Commercial/Industrial)
H_b	(Building height)	= 488 cm (Residential) = 244 cm (Commercial/Industrial)
ACH	(Indoor air exchange rate)	= 1/hour (Residential) = 2/hour (Commercial/Industrial)

The total building air volume for the Tier 1 residential and commercial/industrial RBSLs are determined from the dimensions of these buildings given previously. Air exchange is considered the principle mechanism for diluting indoor air contaminant concentrations since contaminant levels in the outdoor air are assumed to be zero for purposes of Tier 1 RBSL development. The ACH is expressed in terms of air changes per hour (i.e., h^{-1}), and is defined as the number of times in an hour that a volume of outside air equal to the internal volume enters the building (Mueller et al. 1988). In general, the ACHs of buildings are dependent on three processes: (1) mechanical or forced ventilation, (2) natural ventilation, and (3) infiltration. Mechanical ventilation is typically required for larger buildings where a certain amount of outdoor air is required for health and comfort. However, the Bureau of Construction Administrators (BOCA) National Mechanical Code requires an ACH of 0.35/hour for residential living areas of single and multiple private dwellings.

Natural ventilation refers to air moved into and out of a space through intentionally provided openings, such as windows and doors, or through nonpowered ventilators (e.g., operating fireplaces increase

ventilation). Natural ventilation processes can vary broadly and depend on the weather, occupant behaviors and activities. As a result, they are difficult to account for in developing a standard default value. Nonetheless, it is reasonable to assume that these processes increase ventilation above that required through mechanical means.

The ACH of a building is also influenced by "infiltration", defined as the uncontrolled airflow through cracks or other unintentional openings. Infiltration of air is influenced by wind, temperature differences and operation of mechanical ventilation systems and appliances which all create pressure differences across the building envelope. Depending on the indoor-outdoor pressure differential air flow will occur through any openings in the structure, which in turn affect the ACH. Much of the airflow is attributable to building construction methods and materials [e.g., building shape, surface area, orientation to prevailing winds, height (buoyancy of warm air), and location of doors and windows].

Scientific publications summarized in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Fundamentals Handbook (ASHRAE, 1993) indicates that residential ACH values can vary widely. Typical ACH values for housing in North America vary considerably, from tight housing construction with seasonal ACHs of about 0.2 to housing with ACHs of 2.0/hour. Individual studies (Grimsrud et al. 1983; Grot and Clark, 1981) summarized by ASHRAE and in the EPA Exposure Factors Handbook (1996) reported **geometric mean** ACH values of 0.53 +/- 1.71 and 0.9 +/- 2.13. The ACH of 0.53 represented energy efficient homes, while 0.9 ACH was for older, lower-income houses [Note: Geometric means are always less than arithmetic means].

Koontz and Rector (1995) compiled data from various projects (2,971 measurements) across the U.S. where perfluorocarbon tracer techniques (PFT) were used. These data were compiled into a PFT database. A review of Table 16-8 in the EPA Exposure Factors Handbook shows that very little information on ACH was obtained during the summer months from houses in northern climates. From this composite data Koontz and Rector (1995) documented 0.45/hr ACH as the 50th percentile. The data are noted as being weighted to compensate for the geographic imbalance in locations where PFT measurements were taken. Data from Michigan is not included in this database, though several northern states were listed.

Single family detached homes without house tightening measures have ACHs ranging from 0.5 to 1.5/ hour (Mueller et al, 1988). The same article gives ranges for single-family attached houses, mobile homes and apartments of 0.35 to 1, 0.3 to 1.5, and 0.3 to 0.9, respectively. It also states that ACHs for "typical residences" range between 0.7 to 1.1. Recent information on ACHs in residences and office buildings has been published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in an August, 1996 Public Review Draft of Standard 62-1989R, *Ventilation for Acceptable Indoor Air Quality*. Pandian et al. (1993) reviewed data on 1,836 U.S. residences (locations not specified). ACH values were as low as 0.1/hr, with approximately half of the observations ranging from 0.35 to 2.35/hr with an arithmetic mean of 2.0/hr and standard deviation of 3.3/hr. ACHs changed considerably with seasons; mean values for fall (0.4/hr), winter (0.5/hr), spring (1.9/hr) and summer (5.4/hr) were reported. Mean ACH values in two-level homes (2.8/hr) were higher than those in single-level homes.

Given the wide variability in ACH values, a default annual ACH of 1.0/hr was selected for residential land use. A default value of 2.0/hour was chosen for commercial/industrial. This is based on simple system rates for total supply air in a general office (ASHRAE, 1996) of approximately 1.0/hour, and considering that ACHs above mechanical system requirements are expected from natural ventilation,

infiltration and occupancy entrance and egress. In general, choosing any reasonable value within the ranges noted above has only a modest effect on the final estimated indoor contaminant concentration (EPA, 1992).

Building Foundation Thickness (L_{crack})
The default value of 15 cm (approximately 6 inches) is based on common construction code requirements.

Source-Building Separation Distance (L_T)
The distance between the contaminant source in soil or groundwater and the building foundation floor for each generic land use scenario is illustrated in Figure 1 and 1a of the "Background and Conceptual Site Models" section. For Tier 1 RBSL application, contaminated soil must be assumed to lie immediately below the building foundation floor. Contaminant sources in groundwater are assumed to be located 115 cm from the **top** of the foundation floor for residential dwellings, and therefore 300 cm below ground surface considering that the basement is 200 cm below grade. This shallow groundwater depth assumption is consistent with depths to groundwater in Michigan while the 100 cm distance between the source and the foundation is established to allow for seasonal fluctuations in the groundwater without direct entry of groundwater into the basement. Because the generic commercial/industrial building is a slab-on-grade, the L_T is 300 cm.

Soil Vapor Convective Flow Rate (Q_{soil})
As noted previously, the JEM incorporates both "diffusive" and "convective" mechanisms of vapor transport. The parameter, Q_{soil} , in the attenuation coefficient equation represents the convective flow rate of contaminant vapors in soil surrounding the subgrade floor and/or walls, through floor/wall cracks into the building. Although the transport of contaminant vapors through soil into buildings can occur solely by molecular diffusion, pressure-driven flow (i.e., convection) may be the principal means by which soil vapors enter buildings. In fact, convective flow of soil gas has been shown to be the dominant mechanism for radon transport into houses (Nazaroff et al. 1985; Nazaroff, 1988). In addition, modeling, field and experimental evidence with tracer gases and actual contaminants have also demonstrated the significance of convective vapor transport (Nazaroff et al. 1987; Little et al. 1992; Garbesi and Sextro, 1989). Calculation of the convective soil vapor flow rate is as follows:

$$Q_{soil} = \frac{2\pi \Delta P k_v X_{crack}}{\mu \ln[2Z_{crack} / r_{crack}]} \qquad (15a)$$

where,

Q_{soil}	(Volumetric flow rate of soil vapor into the building)	= 0.81 cm^3/s (Residential) = 2.09 cm^3/s (Commercial/Industrial)
ΔP	(Soil column-building dynamic pressure differential)	= 10 g/cm-s (1 Pascal)
k_v	(Soil vapor permeability)	= 5E-9 cm^2
X_{crack}	(Total floor/wall seam perimeter distance)	= 4224 cm (Residential) = 7712 cm (Commercial/Industrial)
μ	(Vapor viscosity of air)	= 1.8E-4 g/cm-s
Z_{crack}	(Crack depth below grade to bottom of enclosed space floor)	= 200 cm (Residential) = 15 cm (Commercial/Industrial)

r_{crack} (Crack radius) = 0.05 cm

This equation is an analytical solution for vapor flow, solely from pressure-driven air flow, to an idealized cylinder buried at a fixed depth (Z_{crack}) below ground surface. The length of the cylinder is equal to the building floor-wall seam perimeter (X_{crack}). Therefore, the default values for X_{crack} are a function of the generic land use-based building floorspace area. Likewise, the default values for Z_{crack} correspond to the residential and commercial/industrial generic buildings described earlier (See Figures 1 and 1a). The cylinder represents the portion or area of the building below grade through which vapors pass (i.e., A_b). The cylinder is considered to represent one of two potential types of openings for soil vapor entry as presented by Nazaroff (1988): (1) a floor-wall joint that is typically found with poured concrete floor and walls, or (2) a perimeter drain-tile system connected through an untrapped line to a basement sump. The radius of the floor-wall seam crack (r_{crack}) is given by:

$$r_{crack} = \eta A_b / X_{crack} \quad (15b)$$

where,

$$\eta = A_{crack} / A_b \ , (0 \le \eta \le 1) \quad (15c)$$

The parameter r_{crack} is the product of the fixed crack to total area ratio (η), and the hydraulic radius of the idealized cylinder, which is equal to the total area of the building below grade (A_b) divided by the portion of the cylinder perimeter in contact with the soil vapor (X_{crack}). The default value for η is given as a ratio of the total crack area (A_{crack}) to the total area of the building below grade (A_b). That is, η represents the fraction of the total subgrade structure area through which soil vapors pass. Grimsrud et al. (1983) empirically determined from leakage area experiments on houses that crack area (A_{crack}) to total floorspace area ranges from 0.01 to 0.1 percent. Sample calculations for this range of η were completed to assess the reasonableness of the total crack area values generated for both generic land uses. the low end of the range, η = 0.01%, was selected as a default as it corresponds to a reasonably conservative total open area of 30.4 in^2 (196 cm^2) for the Tier 1 residential scenario. For consistency, an η of 0.01% is also used for the Tier 1 commercial/industrial criteria. Incorporating this default value into the above equation allows for calculation of the total crack area as follows:

$$A_{crack} = \eta A_b \quad (15d)$$

Indoor-Outdoor Pressure Differential (ΔP)

Convective transport of soil contaminant vapors into buildings occurs as the result of depressurization (i.e., negative pressure) of the subgrade portion of the building relative to the pressure in the surrounding soil (Garbesi and Sextro, 1989). This indoor-outdoor pressure differential (ΔP) which drives the flow of vapors into the building is caused by meteorological, mechanical and occupant behavior factors. The meteorological factors include indoor-outdoor temperature differences ('stack effect'), wind loading on the building superstructure and barometric pressure changes. Examples of mechanical and occupant behavioral factors that lead to unbalanced ventilation include the operation of exhaust fans, ceiling fans, fireplaces and oil/gas furnaces. The building type, design, materials and workmanship (relative to the tightness of the construction) also influence building pressures.

ASHRAE (1993) indicates that wind driven pressure typically averages less than 2.5 Pascal's (Pa) [1 Pa = 10 g/cm-s]. A recent article by Fisher et al. (1996) estimated depressurization in a California home to be approximately 3 Pa due to average wind loading. Negative pressure produced from heating has been reported by Nazaroff et al. (1985). Values of ΔP measured from February through May (15 samples) in a Chicago detached one-story house with a basement (characteristic of the residential generic) built in the 1950's ranged from 0.6 to 4.3 Pa with a mean of 2.3 Pa. These values are considered seasonal, as ΔP values attributable to temperature in the non-heating season would be zero or positive. The effect of operating mechanical ventilation systems is reported to range from 3 to 6 Pa (ASHRAE, 1993). Lindmark and Rosen (1985) note that indoor atmospheres usually maintain a negative pressure of 0-2 Pa, though pressures three times this may be found in dwellings having mechanical ventilation and good insulation.

Collectively, this information indicates that some degree of negative pressure should be incorporated into the Tier 1 RBSL calculations as an annual default value. Characterizing the extent of depressurization for an annual period and representing the various factors is a highly uncertain process. Due to this uncertainty and the inability to estimate the simultaneous interactions of these factors, a default value for ΔP of 1 Pa is chosen to preclude exaggerating the impact of this variable on the calculated criteria.

Soil Vapor Permeability (k_v)

Soil vapor, or soil air permeability (k_v) is a measure of the resistance to air flow in a porous medium; the greater the vapor permeability, the lower the resistance. Generally, k_v is a function of soil type and more specifically grain size and shape (EPA, 1995). As illustrated by Johnson and Ettinger (1991) the k_v has a significant effect on the *convective* soil vapor flow rate into the building, Q_{soil}, thus a large effect on the attenuation coefficient (α). Because k_v is one of the most sensitive parameter in the JEM, a conservative default value must be chosen for generic application and criteria development.

Therefore, a slightly more conservative soil type than the generic loam soil type used in recent Tier 1 RBSL developed by the MDEQ (1997a,b,c) was used to develop the default k_v value. In addition, k_v is specific to soils directly adjacent to the subgrade portion of the building, specifically those soils within the 'zone of influence' as illustrated in Figures 1 and 1a. These (backfill) soils are typically of a higher sand content to ensure adequate drainage of water from soil next to the foundation floor and walls. Therefore, "sandy loam" was selected as the soil type for calculation of the default k_v value. A method described by EPA (1995) along with the soil physical characteristics data for sandy loam from Carsel and Parrish (1988) was used to estimate. Attachment 2 lists the default input parameter values for the soil characteristics of sandy loam that are needed to derive the default k_v value. The default soil parameter input values are also provided in the attachment for the remaining 11 SCS soil textural classifications. The default k_v value is calculated as follows:

1. The "intrinsic" soil permeability is calculated as:

$$k_i = \left(\frac{k_s \times \mu_w}{\rho_w \times g} \right) \times \frac{1}{3600\, s/hr} \qquad (16)$$

where,

k_i	Intrinsic soil permeability	= cm^2
k_s	Saturated hydraulic conductivity	= 4.42 cm/hour (Carsel & Parrish,1988)
μ_w	Dynamic viscosity of water	= 0.01307 g/cm-s
ρ_w	Density of water	= 0.999 g/cm^3
g	Acceleration due to gravity	= 980.665 cm/s^2

The calculated value for k_i, which is a property of the soil alone that varies with the size and shape of the connected pore openings, is therefore equal to 1.64E-8 cm^2.

2. The relative vapor permeability is next calculated and is written as:

$$k_{rg} = (1 - S_{te})^{0.5} \times \left(1 - S_{te}^{1/M}\right)^{2M} \qquad (17)$$

where,

k_{rg}	Relative air permeability	= unitless
S_{te}	Water-filled porosity	= 0.644 unitless (see equation 18 below)
M	van Genuchten water retention parameter	= 0.471 unitless (Carsel & Parrish, 1988)

and,

$$S_{te} = \frac{\theta_w - \theta_r}{n - \theta_r} \qquad (18)$$

where,

θ_w	Soil water-filled porosity	= 0.3 cm^3/cm^3
θ_r	Residential soil water content	= 0.065 cm^3/cm^3 (Carsel & Parrish, 1988)
n	Total soil porosity	= 0.43 cm^3/cm^3

Therefore, $k_{rg} = 0.0.373$.

Finally, the soil air permeability (k_v) is calculated as:

$$k_v = k_i \times k_{rg} \qquad (19)$$

k_v = 6.1E-9 cm^2

To avoid implied precision in a parameter that can vary widely within a small area, the default k_v value is set at 5E-9 cm^2 (the mid value between 1E-8 and 1E-9 cm^2) for calculation of the Tier 1 RBSL GVIIC and SVIIC.

The above procedure used to derive the default k_v value for soil in contact with the subgrade portion of the building assumes homogeneous soils. Though this may, be conservative assumption in some cases, it is equally important to note that the equations do not account for preferential vapor migration that may occur as a result of soil fractures, vegetation root pathways, or the effects of a gravel layer or backfill that may increase the vapor permeability of these soils, thereby increasing the soil gas entry flow rate into the building (Q_{soil}).

Finite Source Soil Volatilization to Indoor Air Inhalation Criteria

Equation 8 above, calculation of the attenuation coefficient (α), does not account for depletion of the contaminant source over time. That is, an infinite contaminant source is assumed. Johnson and Ettinger (1991) provide a finite source method which can be used if the vertical thickness of soil contamination is known. A time-average finite source attenuation coefficient, $\prec\alpha\succ$, can be calculated to account for depletion of the contaminant vapor source over time. Calculations performed assuming a two meter source thickness in the equations below revealed negligible differences between the finite and infinite SVIIC for the majority of chemicals. Notable differences existed for only the highly volatile chemicals (approximately 12 chemicals). Therefore, finite Tier 2 SSTL SVIIC are not provided in the Tier 1 RBSL Tables.

The method outlined below cannot be used for groundwater. Depletion of a groundwater contaminant source over time is more difficult to determine due to the continuous movement of groundwater and the uncertainty of the source characteristics.

Although many processes can contribute to source fluctuations over time, such as biodegradation, chemical interaction and transport away from the source, only the latter is currently incorporated into the finite source method presented below. Implicit in this approach is the assumption that depletion occurs first from contaminant nearest the building floor, and a hypothetical depletion zone increases in thickness over time (Johnson and Ettinger, 1991). Since the JEM considers vapor migration in one dimension it is important that the vertical thickness of the source be adequately characterized throughout the site. Depending on the vertical thickness of the contamination, contaminant of concern, and land use-specific exposure period, the time required for source depletion (τ_D) may be less than the time period over which exposure is averaged. The time required to deplete a finite source (τ_D) of thickness ΔH_c is given as:

$$\tau_D = \frac{\left[\ \Delta H_c / L_T^0 + \beta\ \right]^2 - \beta^2}{2\psi} \qquad (20a)$$

where,

ΔH_c	(Thickness of soil contamination)	= site-specific, cm
L_T^0	(Source-building separation at time (t) = 0)	= site-specific, cm

and,

$$\beta = \left(\frac{D_v^{eff} A_b}{L_T^0 Q_{soil}}\right)\left[1 - \exp\left(-\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)\right] + 1 \qquad (20b)$$

and,

$$\psi = \left[\frac{D_v^{eff} CR_{source}}{\left(L_T^o\right)^2 \rho_b C_s}\right] \times 10^3\ g/kg \times 10^{-6}\ m^3/cm^3 \qquad (20c)$$

where,

D_v^{eff}	(Effective diffusion coefficient through vadose zone)	= chemical-specific (cm^2/s)
CR_{source}^{soil}	(Vapor phase concentration to total soil source concentration ratio)	= Chemical specific, $(ug/m^3)/(ug/kg)$ (see Equation 6)
A_b	(Area of enclosed space below grade)	= 1.96E+6 cm^2 (Residential) = 3.72E+6 cm^2 (Commercial/Industrial)
Q_{soil}	(Volumetric flow rate of soil vapor into the building)	= 0.81 cm^3/s = 2.09 cm^3/s
L_{crack}	(Building foundation thickness)	= 15 cm
D^{crack}	(Effective diffusion coefficient through crack)	= cm^2/s, ($D^{crack} = D_v^{eff}$, see equation 9)
A_{crack}	(Total area of cracks below grade)	= 196 cm^2 (Residential) = 372 cm^2 (Commercial/Industrial)
ρ_b	(Soil dry bulk density)	= 1.5 g/cm^3
C_s	(Initial average contaminant level in soil at time (t) = 0)	= 1 ug/kg

If the exposure averaging period (τ) is greater than or equal to τ_D the average building indoor vapor contaminant concentration to the soil vapor phase source concentration ratio ($CR_{building}$) is adjusted for incorporation into equation 1 or 2, as follows:

$$CR_{building} = \left[\left(\frac{\rho_b C_s \Delta H_c A_b}{\tau}\right) \times 10^{-3}\ kg/g\right] \times \left(\frac{1}{Q_{building}}\right) \times 10^6\ cm^3/m^3 \qquad (21)$$

where,

$CR_{building}$	(Ratio of indoor vapor concentration to soil or groundwater vapor source concentration)	= chemical-specific, $(ug/m^3)/(ug/kg)$
τ	(Exposure averaging period)	= 9.5E+8 s (Residential, i.e., 30 years) = 6.6E+8 s (Commercial/Industrial)
$Q_{building}$	(Building ventilation rate)	= 1.51E+5 cm^3/s (Residential) = 5.04E+5 cm^3/s (Commercial/Industrial)

Though unnecessary for calculation of finite source SVIIC, the long-term average attenuation coefficient may be derived as follows:

$$\prec \alpha \succ = \frac{\rho_b C_s \Delta H_c A_b}{Q_{building} CR_{source}^{soil} \tau} \left(\frac{L_T^0}{\Delta H_c} \right) \left[\left(\beta^2 + 2\psi\tau \right)^{1/2} - \beta \right] \times 10^{-3} \text{ kg/g} \times 10^6 \text{ cm}^3/\text{m}^3 \qquad (22)$$

APPLICATION AND IMPLEMENTATION

The purpose of the Part 213 Tier 1 RBSLs for GVIIC and SVIIC is to identify sites where contaminant concentrations in groundwater or soil may be sufficient to pose unacceptable inhalation risks from the intrusion and accumulation of contaminant vapors in buildings. These values can be used for determining whether a property is a facility under Part 201, and are relevant in determining the adequacy of a CAP or evaluating the need for corrective action activities.

The Tier 1 RBSLs are generated from a series of calculations which make a number of generic assumptions related to the contaminant source, soil, groundwater and building characteristics, and human exposure potential. Figures 1 and 1a (the generic CSMs) illustrates the assumptions used in the development of the Tier 1 RBSLs . The quantitative method and default assumptions provide reasonably conservative criteria.

⇒ **Note:** Further evaluation of indoor air inhalation risks is not required at sites with concentrations less than these values, unless one or more of the following conditions exist, in which case, the Tier 1 RBSLs for GVIIC and/or SVIIC do not apply and a site-specific evaluation must be conducted.

- A structure is present or is planned for construction that uses materials at or below grade, such as soil or stone for floors or walls, that does not provide an equivalent limitation on vapor infiltration as is provided by poured or concrete block floor or walls.
- A sump is present that is not completely encased from the surrounding soil by construction materials.
- For the GVIIC, the highest groundwater table elevation, considering seasonal variation, is less than three meters below grade, or there is direct entry of contaminated groundwater into the building, such as seepage or through the foundation floor, walls, drains or a sump opening.
- For the GVIIC, there is free-phase liquid hazardous substance present on or above the groundwater table.
- For the SVIIC, there is a hazardous substance present in soil above the C_{sat} concentration for that substance, or non-aqueous phase liquids (NAPLs) are present.

In all cases, it is important that users consult with STD staff when addressing site situations that are NOT represented by the generic assumptions inherent to these criteria. For example, these criteria may not be appropriate at facilities where site investigations reveal that foundation floors and/or walls are in poor condition, or other openings exist such as around utility line entry points.

For LUST sites where the business, also includes the servicing of motor vehicles inside the building, it may not be feasible to distinguish with reasonable certainty between the exposure from daily operating activities and the contribution potentially occurring from contaminated soil or groundwater existing at the site. Therefore, a quantitative evaluation of the indoor air inhalation pathway from soil or groundwater is not required if all of the following conditions are satisfied:

1. The site building is on a slab foundation
2. Off-site locations do not exceed the Tier 1 unrestricted residential use for soil and groundwater indoor air concentrations.
3. The present site use remains an active motor vehicle servicing operation and closure is based on institutional controls (Notice of Notice of Corrective Action or Deed Restriction). If the use of the site should change, the site must be evaluated in accordance with the RBCA process, consistent with the proposed change in use.

For all other sites, a complete evaluation of the indoor inhalation pathway must be performed.

GVIIC Applications

The groundwater volatilization to indoor air pathway is relevant at sites where groundwater is present. The Tier 1 RBSL criteria assumes that the depth to the groundwater tables is three (3) meters below grade. Where the groundwater table elevation is greater than three (3) meters below grade, the Tier 1 GVIIC are applicable to all depths within the groundwater saturated zone. Where the groundwater table is less than three (3) meters below grade, site-specific values must be determined, and would be applicable to all depths within the groundwater saturated zone. In the case where groundwater is of insufficient quantity (see STD Operational Memorandum No. 11), professional judgment can be used to determine if the GVIIC pathway is relevant and supported by appropriate documentation in the CAP or Closure Report.

Site-Specific Unrestricted Closures

Due to wide variation in site-specific soil characteristics and exposure settings, it is probable that the generic assumptions may not accurately represent the conditions at certain sites. For these cases, site-specific values (Tier 2 evaluation) may be used in place of the generic assumptions and still allow unrestricted closures. The three soil parameters listed below may be substituted, as a group, in place of the generic values.

- Soil vapor permeability (k_v)
- Soil dry bulk density (ρ_b)
- Soil organic carbon content (f_{oc})

The default soil water-filled porosity (θ_w) and soil air-filed porosity (θ_a) values represent soil not covered by a building. Since infiltration of water into soil (soil moisture recharge) below a building will be reduced for most structures, θ_w and θ_a should not be made less conservative. Therefore, modification of θ_w and θ_a is not appropriate.

Unrestricted closures can also be obtained by replacing the generic values with the site-specific values for the following parameters:

- Chemical-specific Temperature Adjustment Factor (TAF) for the Henry's Law Constant
- Source-building foundation separation distance (L_T) for GVIIC only (Generic building assumptions cannot be changed)
- Vertical thickness of capillary fringe (h_t) for GVIIC only
- Vertical thickness of soil contamination (ΔH_c) for finite source SVIIC only

Supporting documentation for all site-specific default value(s) must be provided in the CAP or STD Closure Report.

Modification of the generic building or human exposure assumptions cannot be made for a site-specific Tier 1 closure. Modification of these assumptions will require closure under section 21310a, such that proper administrative mechanisms are in place to assure that future site conditions will remain consistent with the site-specific assumptions.

Options for Demonstrating Compliance

There are a number of approaches that may be considered to demonstrate protection against unacceptable indoor air inhalation risks once it is determined that one or more of the individual site sample concentrations do not meet the relevant land use-based Tier 1 RBSLs for GVIIC and/or SVIIC.

More detailed modeling approaches may be used to satisfy the requirements of a site-specific Tier 1 closure. Justification must be provided describing why the proposed model is more appropriate to the site in question than the JEM. The proposed model must be documented and shown to be mathematically sound, and account for both diffusive and convective vapor transport mechanisms.

Statistical evaluation of site data may be conducted to demonstrate compliance with the Tier 1 RBSLs . Statistical analysis of site data must not encompass areas larger than the relevant generic land use building footprint size (i.e., residential - 1,200 ft^2; commercial/industrial - 4,000 ft^2). In addition, if there are groundwater and soil sample concentrations greater than water solubility or C_{sat} concentrations, respectively, statistical analysis is not appropriate as the equilibrium partitioning equations of the JEM are not valid at such levels.

Soil gas measurements may also be used to demonstrate a site-specific Tier 1 closure. If collected properly, soil gas sampling should more accurately represent the soil vapor contaminant concentrations that are subject to the convective transport mechanisms attributable to the soil vapor permeabilities and building pressure influences on the surrounding soil. Soil gas measurements/data cannot be incorporated into the Tier 1 RBSL equation framework presented above, since soil gas measurements are reported as concentrations whereas "concentration ratios" are used here for purposes of back-calculating acceptable soil and groundwater concentrations. A methodology, however, has been developed using aspects of the JEM and risk assessment equations to calculate soil gas concentrations protective of unacceptable indoor air inhalation risks (Attachment 3). This method is only applicable for demonstrating compliance with the SVIIC; a method may be developed in the future to demonstrate compliance with the generic GVIIC.

Due to the heterogeneity of physical soil characteristics, it is expected that soil gas concentrations will vary considerably with location and time of collection. As a result, it is necessary to collect soil gas

samples at various points around the building, and to conduct a minimum of two sampling events. The use of soil gas probes is recommended, with a minimum of two sampling points on each side of the building. One additional sample should be obtained from directly beneath the building, nearest to center as possible. This satisfies statistical concerns documented in EPA (1990) indicating that this sample size is sufficient for calculating the mean concentration within 20 percent of the 95% upper confidence level. ASTM (1997) provides guidance for conducting soil gas monitoring.

To determine the resulting soil vapor infiltration rate it is necessary to obtain measurements of the soil vapor permeability (k_v) at each of the probe locations. Values of k_v will indicate whether infiltration of vapors into the building are likely to occur by diffusion or convection. Probes should be installed so that the probe tips are between 50 and 100 cm from the floor or basement wall. For Tier 1 commercial/industrial buildings that are assumed to be slab-on-grade, probes should be positioned at an angle to reach under the building.

Other Closure Options

A party may elect not to comply with the Tier 1 RBSLs for GVIIC or SVIIC, but show through an adequate indoor air monitoring plan that the building contaminant concentrations are below acceptable levels. The acceptable indoor air concentration for a given contaminant is determined by eliminating the parameter $C_{building}$ from equations 1 through 4. An adequate sampling plan is one that obtains measurements that account for potential changes to indoor air concentrations resulting from seasonal (i.e., climatic) changes. Therefore, a single sampling event is not acceptable.

Unfortunately, monitoring indoor air alone is only useful if it shows negative results, as detection above acceptable indoor air concentrations elicit a need to identify the source of the contamination. It cannot be concluded that indoor air detection is the result of soil contaminant vapor infiltration unless ambient air measurements and evaluation of household sources are ruled out. Optimally, indoor air monitoring combined with ambient air and soil gas measurements provide the necessary database for assessing the potential impact of subsurface contamination on the indoor air quality of buildings. Sampling of contaminant concentrations in these three areas should take place within a 12-hour period, since significant changes in barometric pressure or measurable rainfall could affect the results. Further guidance on indoor air sampling protocols and analyses are provided in EPA (1990, 1992) guidance.

Installing and maintaining vapor barriers is another means for obtaining a limited land use closure. Vapor barriers may consist of simple measures such as sealing off soil vapor entry routes or engineered mitigation technologies designed to divert or vent contaminant vapors away from the building. One may also opt to allow contaminant vapors to enter, but control contaminant concentrations at acceptable levels through ventilation or dilution techniques. Details of these mitigation strategies can be found in EPA (1993) guidance.

In some cases, it may be preferable to limit exposure through restrictions on property use. Deed restrictions can be placed on the property in question to prevent construction of buildings

An alternative to complying with the GVIIC at all groundwater depths may be possible in certain situations if reliable controls and monitoring are implemented to assure that upward migration of groundwater contaminants does not occur.
A site-specific evaluation to document that conditions at a site do not result in an unacceptable exposure may be based on demonstration of compliance with Act No. 174 of the Public Acts of 1974, as amended, being Section 408.1001 et seq. of the Michigan Compiled Laws, and known as the Michigan

Occupational Health and Safety Act, and the rules promulgated pursuant to that Act. This approach would be handled as a site-specific closure in accordance with Section 21310a(2), that would require a restrictive covenant filed with the deed. Site-specific criteria developed pursuant to this provision shall apply when all of the following conditions are satisfied:

a) The risk being evaluated results from inhalation by workers of hazardous substances in indoor air within an active commercial or industrial workplace that is regulated by the Michigan Occupational Safety and Health Act, and the rules promulgated pursuant to that Act.
b) The exposure to hazardous substances from environmental contamination is a portion of the exposure to which workers are otherwise subject from process-related sources of the same hazardous substance.
c) The risk to the non-worker population, if any, from inhalation of indoor air at the site has been evaluated according to risk assessment methods acceptable to the department, and the risk is not unacceptable on the basis of the risk management objectives set forth in Section 21304a of Part 213.

Chemicals of Concern

Tier 1 RBSLs are ***not*** presented in the revised Part 213 Tier 1 RBSL Tables for all hazardous substances currently regulated. This is because some substances either do not volatilize (elemental inorganics) or volatilize at such low levels that their vapor phase concentration would not exist at a sufficient level to pose a health risk. Chemicals of concern for this pathway were identified as those having a Henry's Law Constant equal to or greater than 1E-5 atm-m^3/mol at standard temperature and pressure (Jury et al. 1983, 1984a,b,c). Chemicals that are designated 'ID' (insufficient data) are lacking one or more of the chemical specific property values needed to calculate a criterion.

Soil Saturation and Water Solubility Limits

The Tier 1 RBSLs for SVIIC default to the soil saturation limit when the Tier 1 RBSLs for SVIIC is greater than Csat. Therefore, it is necessary to compare the SVIIC with its corresponding Csat value. The Csat values published in the revised Tier 1 RBSL Tables differ slightly from the values documented in the September 4, 1996 Operational Memorandum No. 4 Attachment 6 document. This is due to the use of soil physical parameter default values representative of subsurface soil conditions instead of surficial conditions, and incorporation of the soil temperature adjustment factor to the HLCs to be consistent with that used to calculate the GVIIC and SVIIC. The Tier 1 RBSLs for GVIIC greater than the water solubility default to the water solubility value as the applicable criterion. These default approaches are necessary as the equilibrium partitioning aspects of the criteria calculations (i.e., C_{source}) are not applicable at concentrations greater than Csat and water solubility for soil and groundwater contaminants, respectively.

This Attachment 8 to Operational Memorandum No. 4 is intended to provide guidance to QCs and STD staff to foster consistent application of Part 213. This document is not intended to convey any rights to any parties, nor create any duties or responsibilities under law. This document and matters addressed herein are subject to revision.

Questions concerning this operational memorandum should be addressed to the appropriate STD project manager or District Supervisor at the district office responsible for the area where the site is located.

Periodic review and revisions to this operational memorandum are the responsibility of the Chief of the Field Operations Section.

Authorization:	**Date**

Distribution: Qualified UST Consultants
STD Mailing List
DEQ Division/Office Chiefs
STD Supervisors

Attachments

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Attachment 1

Thickness of Capillary Fringe - h_{cf}

Table 1. Height of capillary rise in sample having virtually the same porosity, 41 percent, after 72 days (Source: Ground-Water Hydraulics, S.W. Lohman, Geological Survey Professional Paper 708).

Material	Grain Size, mm	Capillary Rise, cm
Fine gravel	5-2	2.5
Very coarse sand	2-1	6.5
Coarse sand	1-0.5	13.5
Medium sand	0.5-0.2	24.6
Fine sand	0.2-0.1	42.8
Silt	0.1-0.05	105.5
Silt	0.05-0.02	200[a]

[a] Still rising after 72 days.

Table 2. Capillary rise in sediments (Source: Applied Hydrogeology, 3rd Edition, Prentice Hall, C.W.Fetter).

Material	Grain Size, mm	Capillary Rise[b], cm
Fine gravel	5	1.5
Very coarse sand	2	4
Coarse sand	0.5	15
Medium sand	0.3	25
Fine sand	0.15	50
Very fine sand	0.075	100
Coarse silt	0.025	300
Fine silt	0.008	750

[b] Capillary rise (H_c) values calculated as:

$$H_c = \frac{2\sigma \times Cos\lambda}{\rho_w \times g \times R}$$

where,

σ	surface tension of water	= 73 g/s^2
λ	angle of meniscus with capillary tube walls	= 0 (Therefore Cos of lambda = 1)
ρ_w	density of water	= 1 g/cm^3
g	acceleration due to gravity	= 980 cm^2
R	radius of capillary tube	= 0.2 x assumed grain diameter

Attachment 2

Mean values of the van Genuchten soil moisture retention and relative permeability parameters for the U.S. Department of Agriculture soil types (EPA, 1995; modified from Carsel and Parrish, 1988)

Soil Texture (USDA)	Saturated Hydraulic Conductivity (cm/hr)	Saturated Water Content θ_s	Residual Water Content θ_r	van Genuchten Parameters			Number of Samples**
				α (1/cm)	N	M	
Clayey Soil*	0.2	0.38	0.068	0.008	1.09	0.083	400
Clay Loam	0.26	0.41	0.095	0.019	1.31	0.237	364
Loam	1.04	0.43	0.078	0.036	1.56	0.359	735
Loamy Sand	14.59	0.41	0.057	0.124	2.28	0.561	315
Silt	0.25	0.46	0.034	0.016	1.37	0.27	82
Silt Loam	0.45	0.45	0.067	0.02	1.41	0.291	1093
Silty Clay	0.02	0.26	0.07	0.005	1.09	0.083	374
Silty Clay Loam	0.07	0.43	0.089	0.01	1.23	0.187	641
Sand	29.7	0.43	0.045	0.145	2.68	0.627	246
Sandy Clay	0.12	0.38	0.1	0.027	1.23	0.187	46
Sandy Clay Loam	1.31	0.39	0.1	0.059	1.48	0.324	214
Sandy Loam	4.42	0.41	0.065	0.075	1.89	0.471	1183

* Clay soil refers to agricultural soil with <60% clay.
** Number of samples as indicated with minor exceptions: see Carsel and Parrish (1988).

Note: Loam soil type bolded to indicate parameters values used to calculate the water-filled porosity ($\theta_{w,cf}$) and air-filled porosity ($\theta_{a,cf}$) default values for the capillary fringe. Sandy loam soil parameter values are used to calculate the soil vapor permeability (k_v) default value.

Attachment 3

Method for Calculating Chemical-Specific Soil Gas Concentrations Protective of Unacceptable Indoor Air Inhalation Health Risks: An Option for Demonstrating Compliance with the Soil Volatilization to Indoor Air Inhalation Criteria (SVIIC)

As an example, the acceptable indoor air vapor concentration, $C_{building}$, , for the residential land use exposure assumptions for <u>carcinogenic</u> chemicals is: (*Note that the adjusted inhalation rate, AIR, parameter would need to be multiplied in the numerator for commercial/industrial land use calculations*)

$$C_{building} = \frac{TR \times AT}{IURF \times EF \times ED} = \frac{ug}{m^3}$$

where,

TR	(Target risk)	= 1E-5
AT	(Averaging time)	= 25,550 days (70 x 365)
IURF	(Inhalation unit risk factor)	= chemical-specific, $(ug/m^3)^{-1}$
EF	(Exposure frequency)	= 350 days/year (Residential)
		= 245 days/year (Commercial/Industrial)
ED	(Exposure duration)	= 30 years (Residential)
		= 21 years (Commercial/Industrial)

The acceptable soil gas (vapor) concentration, C_{source}, can be back-calculated given that:

$$C_{building} = \alpha \times C_{source}$$

where,

α	(Attenuation coefficient)	= unitless (see equation 8)

Since the contaminant source is assumed to lie directly below the foundation for generic calculations, the source-building separation distance approaches zero and α can be approximated by $Q_{soil}/Q_{building}$.
Therefore,

$$C_{building} = \frac{Q_{soil}}{Q_{building}} \times C_{source}$$

where,

Q_{soil}	(Volumetric flow rate of soil vapor into the building)	= 0.81 cm^3/s (Residential)
		= 2.09 cm^3/s (Commercial/Industrial)
$Q_{building}$	(Building ventilation rate)	= 1.51E+5 cm^3/s (Residential)
		= 5.04E+5 cm^3/s (Commercial/Industrial)

Algebraically,

$$C_{source} = C_{building} \times \frac{Q_{building}}{Q_{soil}}$$

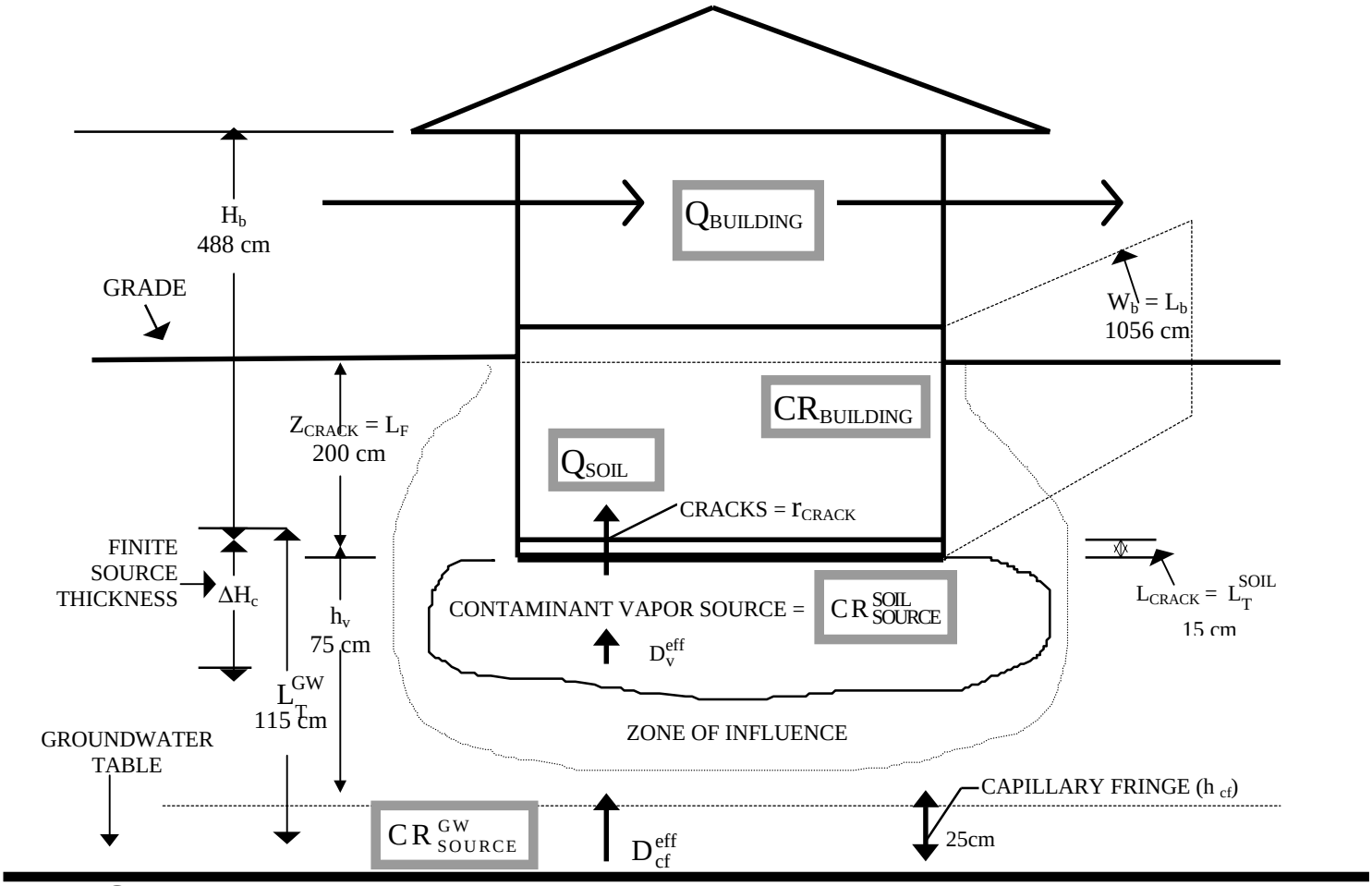
The generic land use-specific default assumptions for Q_{soil} and $Q_{building}$ must be used to derive the correct soil gas concentration, C_{source}, in units of ug/m^3, to comply with the generic SVIIC. These units can be converted to ppm by volume (ppmv), if necessary, for comparison to site-specific soil gas measurements using the ideal gas law as follows:

$$SG = \frac{R \times T}{p \times mw} \times C_{source} \times 10^{-6}\, g / ug$$

where,

SG	Soil gas concentration	= cm^3/m^3 or ppmv (chemical-specific)
R	Universal gas constant	= 82.05 atm-cm^3 /mol-K
T	Absolute temperature	= 293.16 K (20° C)
p	Absolute pressure of gas	= 1 atm
mw	Molecular weight	= chemical-specific (g/mol)

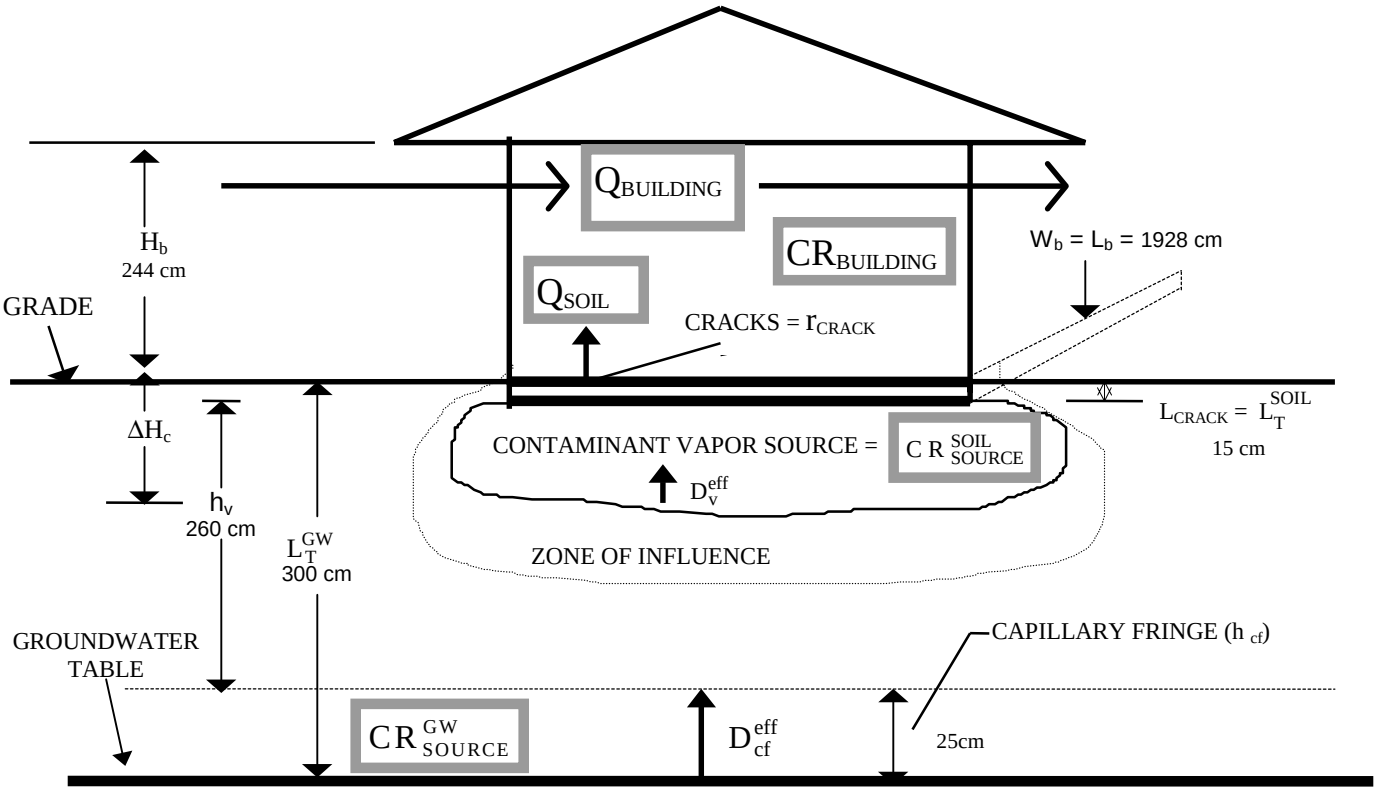
Figure 1
RESIDENTIAL VAPOR INTRUSION
Conceptual Site Model



LEGEND

CR^{GW}_{SOURCE}	Vapor-phase concentration to total groundwater source concentration ratio	h_v	Thickness of vadose zone below enclosed space floor	L_T^{SOIL}	Source-building separation distance for soil
CR^{SOIL}_{SOURCE}	Vapor-phase concentration to total soil source concentration ratio	h_{cf}	Thickness of capillary fringe	L_F	Depth below grade to bottom of enclosed space floor
$CR_{BUILDING}$	Indoor vapor concentration to the vapor-phase source concentration ratio	L_{CRACK}	Building foundation thickness	L_b	Building floor length
Q_{SOIL}	Soil vapor flow rate into the building	Z_{CRACK}	Crack depth below grade to bottom of enclosed space floor	W_b	Building floor width
$Q_{BUILDING}$	Building ventilation rate	r_{CRACK}	Crack radius	H_b	Building floor height
D_{cf}^{eff}	Effective diffusion coefficient through capillary fringe	L_T^{GW}	Source-building separation distance for groundwater	ΔH_c	Vertical thickness of soil contamination for finite source
D_v^{eff}	Effective diffusion coefficient through vadose zone				

Figure 1a
COMMERCIAL/INDUSTRIAL VAPOR INTRUSION
Conceptual Site Mode



LEGEND

CR_{SOURCE}^{GW}	Vapor-phase concentration to total groundwater source concentration ratio	h_v	Thickness of vadose zone below enclosed space floor	L_T^{SOIL}	Source-building separation distance for soil
CR_{SOURCE}^{SOIL}	Vapor-phase concentration to total soil source concentration ratio	h_{cf}	Thickness of capillary fringe	L_F	Depth below grade to bottom of enclosed space floor
$CR_{BUILDING}$	Indoor vapor concentration to the vapor-phase source concentration ratio	L_{CRACK}	Building foundation thickness	L_b	Building floor length
Q_{SOIL}	Soil vapor flow rate into the building	Z_{CRACK}	Crack depth below grade to bottom of enclosed space floor	W_b	Building floor width
$Q_{BUILDING}$	Building ventilation rate	r_{CRACK}	Crack radius	H_b	Building floor height
D_{cf}^{eff}	Effective diffusion coefficient through capillary fringe	L_T^{GW}	Source-building separation distance for groundwater	ΔH_c	Vertical thickness of soil contamination for finite source
D_v^{eff}	Effective diffusion coefficient through vadose zone				